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Functional Relevance of Relative Maintenance of Maximal Eccentric Quadriceps Torque in Healthy Old Adults

Jeroen Waanders Chantal Beijersbergen Alessio Murgia Tibor Hortobágyi

Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

Key Words
Gait velocity · Walking · Stair locomotion · Ramp locomotion · Muscle torque · Aging

Abstract
Background: Old referenced to young adults show a relative maintenance of maximal eccentric (RELM) compared to concentric muscle torque: ~76 and ~59%, respectively. However, it is unknown if RELM affords functional benefits in old adults. ***Objective:*** We examined if there is specificity between the two types of peak quadriceps torque (i.e., concentric and eccentric) and timed gait performance measured during level, ramp, and stair walking and if gait performance was higher in old adults with high versus low RELM. ***Methods:*** We measured peak concentric and eccentric quadriceps torque at 60 and 120°/s and timed gait at habitual and safe-fast speeds in healthy young (age 22.7 years, n = 24) and old (age 70.0 years, n = 21) adults. ***Results:*** Comparable to previous studies, RELM was 21%, but instead of the anticipated specificity, we found that concentric compared with eccentric torque was more strongly associated with gait performance than eccentric torque, independently of walking direction and age (R^2 = 0.16: eccentric vs. descending gaits; R^2 = 0.17: eccentric vs. ascending gaits; R^2 = 0.45: concentric vs. descending gaits; R^2 = 0.56: concentric vs. ascending gaits, n = 45, all p < 0.01). Furthermore, old adults (n = 10) with ~30% greater than normal levels of RELM (n = 11) ambulated at similar velocities measured on level and inclined surfaces. ***Conclusion:*** Normal and 30% above normal levels of RELM do not seem to increase or predict healthy old adults' gait performance on level and inclined surfaces. Future work should examine if RELM is associated with a heightened performance in other measures of neuromuscular function, such as gait biomechanics, muscle activation, as well as rate and control of voluntary force development in old adults with high or low mobility.

Introduction

There is overwhelming evidence that even healthy aging old adults exhibit muscular, neuronal, and cognitive dysfunctions [1–7]. One such impairment is a characteristic and clearly recognizable decrease in the ability to produce maximal voluntary leg muscle torque, starting as early as 50 years of age [1, 5, 6]. A multitude of factors contributes to the evolution of the age-related weakness, dynapenia [8], including a loss of muscle protein content

KARGER

E-Mail karger@karger.com
www.karger.com/ger

Jeroen Waanders
Center for Human Movement Sciences
University Medical Center Groningen, A. Deusinglaan 1
NL–9700 AD Groningen (The Netherlands)
E-Mail j.b.waanders@gmail.com

or sarcopenia [9, 10], neuronal hypoexcitability [11, 12], and a reconfiguration of tendon structure that interferes with the transmission of muscle force to the bony levers [13, 14]. Interestingly, the magnitude of the age-related decline in maximal voluntary quadriceps muscle torque is not uniform across the three main types of muscle contraction. While maximal voluntary quadriceps muscle torque can decline by 50% when the muscle actively shortens [i.e., concentric (CON) contraction] or produces tension at the same length (i.e., isometric contraction) [1, 5, 6, 15], the magnitude of decline when the quadriceps muscle actively lengthens [i.e., eccentric (ECC) contraction] can be as small as 20% [7, 16–18].

Despite differences in how previous studies determined the magnitude of ECC torque maintenance (e.g., contraction velocity and normalization method), calculated as the relative maintenance of maximal ECC (RELM) compared to maximal CON muscle torque in the present study, RELM seems to be a robust phenomenon. That is, it is present not only in healthy aging old adults but also in aging adults with mobility disability and spasticity [16, 19]. For example, paretic and non-paretic lower limb muscles showed a 16 and 14% higher maintenance, respectively, of relative maximal ECC versus relative CON muscle torque in elderly stroke patients compared to healthy age-matched controls [19]. The underlying mechanisms of RELM in old muscles are still unclear, although molecular and behavioral factors have been considered in the form of a slowed detachment rate of active cross-bridges and high fiber stiffness [16]. For reasons that are poorly understood, there is a gender effect in RELM, as a few studies reported actually no age-related decline in maximal voluntary ECC forces measured in females compared to the decline seen in males [7, 17]. For example, old males were able to produce 80% of young males' ECC peak torque, while this amount was 110% in elderly females [7].

In line with the predictions of mobility disability models [20, 21], old adults with high versus low levels of maximal voluntary leg torque ambulate faster, perform activities of daily living (ADL) more easily, and negotiate stairs and ramps with less effort [22, 23]. The functional benefits of a well-maintained ability to generate maximal voluntary torque in old age materialize through the concept of relative effort, showing that old adults often execute ADLs near their maximal available abilities [23]. It is, therefore, a relevant but unexplored question how, if at all, RELM translates into functional benefits and whether such benefits differ between genders. Firstly, we examined the effects of age and gender on peak CON and ECC quadriceps torque as well as on a set of ADL locomotor tasks (level, ascending, and descending gaits). Secondly, we determined the relationship between peak torque and ADL locomotor tasks in young and old adults. Thirdly, we examined the effects of high versus low RELM on ADL task performance. We performed these analyses across a spectrum of torques (ECC, CON) and tasks (level, ascending, and descending gaits) that were similar or dissimilar with respect to the type of muscle contraction to provide evidence for the hypothesis that the relative maintenance of maximal quadriceps ECC torque per se and not just maximal leg muscle torque in general affords functional benefits in old adults.

Methods

Study Design

For this cross-sectional study, subjects reported to the laboratory once for measurements consisting of: (1) maximal quadriceps strength and (2) gait performance, administered in random order. Subjects were recruited from the surrounding communities and shopping malls through word of mouth, flyers, and newspaper advertisements. The Medical Ethics Committee at the University Medical Center of Groningen, Groningen, the Netherlands, approved the study protocol (No.: METc 2015/144), and each subject signed a written informed consent form before the start of the measurements, which were completed according to the Declaration of Helsinki.

Subject Characteristics

Healthy young (n = 24) and healthy, community-dwelling old (n = 21) adults participated in the study. Inclusion criteria were: age 20–30 or over 65 years and being in good health. Exclusion criteria were: joint replacement, amputation, neuromuscular impairments, a history of neurological conditions (stroke, Parkinson's disease, and dementia), pulmonary disease, pregnancy, diabetes with neuropathy in the legs, and a body mass index over 30. In addition, subjects were cognitively healthy, physically active, and did not have mobility disability, according to the Mini Mental State Examination (MMSE), the Short Questionnaire to Assess Health-Enhancing Physical Activity (SQUASH), and the Short Physical Performance Battery (SPPB), respectively (table 1). Body mass was measured to the nearest 0.1 kg on a digital weight scale (Seca 803; Seca GmbH and Co., Hamburg, Germany), and height was measured to the nearest 0.5 cm using a stadiometer (Seca 213).

Isokinetic Dynamometry

Maximal voluntary CON and ECC torque of the right quadriceps were measured using a KinCom isokinetic dynamometer (model AP125; Chattecx Inc., Chattanooga, Tenn., USA), revealing acceptable test-retest reliability of quadriceps torque [intraclass correlation coefficient ranged from r = 0.74 to 0.92 (ECC 180°/s to CON 180°/s)] [7]. The present study focused on the quadriceps, because this muscle group generates and absorbs much of the power in locomotor ADL tasks [24, 25].

Table 1. Subject characteristics

Characteristics	Young (11 F, 13 M)	Old (10 F, 11 M)
Age, years	22.7±2.1	70.0±3.2
Body weight, kg	68.9±8.0	73.4±8.4
Body height, m	1.78±0.07	1.74±0.06
Body mass index	21.9±2.1	24.3±2.3
SPPB score	11.75±0.53	11.29±0.78
MMSE score	29.25±1.19	28.43±1.36
SQUASH		
Total score[a]	8,884±3,749	10,906±4.876
Light, min/week	1,395±855	804±667
Moderate, min/week	285±228	593±575
Heavy, min/week	319±279	578±473

Values are mean ± SD. [a] Total score is expressed as minutes per week × intensity of the activity.

The location of the dynamometer seat and power head was set individually for each subject. During testing, subjects sat with a hip angle of 85° with arms folded in front of the chest and two cross-over upper-body belts, a lap belt, and a thigh strap, minimizing extraneous movements. The transverse axis of the joint was aligned with the rotational axis of the dynamometer's head, and the joint's anatomical zero was set at a joint position corresponding to the leg fully extended. The mass of the lower leg was measured and the dynamometer's software automatically computed torques corrected for leg mass. Range of motion (ROM) was set between 10 and 75° of maximal knee extension. Before testing, subjects performed familiarization trials for both types of dynamic contraction. Subjects were instructed to contract as hard and fast as possible and were verbally encouraged during the test. Two trials were performed at 60 and 120°/s for both CON and ECC conditions, with a 3-second pause between contractions and 1 min of rest between conditions and speeds. The order of muscle contraction type and angular velocity was randomized between subjects.

Gait Performance

Gait performance was measured by recording the time needed to complete 5 standardized locomotion tasks: level walking, stair ascent, stair descent, ramp ascent, and ramp descent. Time to completion was measured with a stopwatch for stair and ramp negotiation, as it is not possible to instrument an entire natural stairwell and ramp with a 3D motion capture system. Subjects performed each task at a habitual and at a safe-fast speed twice. For the habitual conditions, subjects were instructed to walk 'as if you walked to the supermarket', and for the safe-fast speed conditions the instruction was to walk 'as fast and safe as you can but do not run'. Subjects performed one familiarization trial for each task. There were 30 s of rest between trials and 1 min of rest between tasks.

For the level walking task, subjects walked on a well-lighted, linoleum-surfaced laboratory floor. The start and end of the 11-meter-long walkway was marked with a pylon. Subjects accelerated and decelerated over a distance of 3 m before and after a middle 5-meter portion of the walkway where they reached a steady pace gait. During this task, a hip marker was tracked at 100 Hz with an Optotrak motion-capture system to calculate gait speed.

For the ramp tasks, subjects walked on a 20-meter-long non-skid, paved, and semicovered entryway to an indoor parking garage, inclined 13%. At about midway, the walking time was measured with a stopwatch over a 5-meter distance, preceded by 3 m of acceleration and followed by 3 m of deceleration.

For the stair tasks, subjects walked up two flights of non-skid edged indoor stairs consisting of 22 steps in total. While negotiating the stairs, subjects had to take a U-shaped turn on a 1.52 m (depth) by 2.57 m (width) landing after the 11th step of the first flight. Each step had a rise of 0.18 m and a depth of 0.22 m. Subjects were instructed to adopt an alternating step strategy without skipping any step and not to use handrails unless they felt they would lose balance. Time was measured with a stopwatch at the instant the subject's foot came into contact with the surface of the first step and the ground after the last stair step.

Data Analysis

The highest peak torque value from both trials was obtained analyzing the text file exported from the dynamometer with a customized MATLAB script (MATLAB 14b; MathWorks Inc., Natick, Mass., USA, 2000). The CON and ECC torque values of each individual subject were divided by the corresponding mean CON and ECC torque values of the young adults for each speed [7], resulting in a measure of age-related muscle torque maintenance for each speed condition. Previously, the RELM magnitude was expressed as the difference between ECC and CON torque maintenance (in %) [16]. In addition, we normalized the RELM magnitude by CON torque maintenance, i.e., [(ECC – CON)/CON] × 100, to control for CON strength levels. For example, an individual with 90% maximal ECC torque maintenance and 70% maximal CON torque maintenance has a RELM magnitude of 28.6% [(90 – 70)/70 × 100 = 28.6%]. Then, high and low RELM individuals in the old group were identified as having a higher or lower RELM magnitude than the mean of the group, respectively. Habitual gait task performance was determined by computing the average of two trials and maximal performance was the fastest trial. Time to completion during the gait performance tasks was recorded at the closest 0.01 s.

Statistical Analyses

The main analysis was an age (young, old) by gender (male, female) by speed (ECC120, ECC60, CON60, CON120) analysis of variance (ANOVA) with repeated measures on speed, followed by a Tukey's post hoc analysis to determine the means that were different ($p < 0.05$). Independent t tests were performed to test for significant differences between old and young adults on gait performance at habitual and maximal speed, adjusted for body height. An exploratory analysis was performed using simple linear regressions to determine (non-)task-specific relationships between CON and ECC muscle torque (predictors) and level, ascent, and descent locomotion performance (outcomes). Therefore, average scores for CON [e.g., (CON120 + CON60)/2] and ECC muscle torque and for ascent [e.g., (ramp ascent + stair ascent)/2] and descent locomotion were computed for every individual. To test for an age effect, a dummy variable of age (young, old) was used. To test for differences in slopes within a group, paired t tests with a pooled standard error were used. Muscle torque was normalized for height and mass, gait performance only for height. Lastly, independent t tests were performed to test for significant differences be-

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Table 2. Peak quadriceps muscle torques in young and old adults

Muscle contraction	Velocity, °/s	Group	Young (11 F, 13 M)	Old (10 F, 11 M)	Maintenance, % young	Maintenance, % old
ECC	120	M	176±34	161±32	100±19	91±18
		F	145±31	134±29	100±22	92±20
		All	162±35	148±33	100±22	91±21
	60	M	176±33	153±28	100±19	87±16
		F	142±39	136±34	100±28	96±24
		All	160±39	145±31	100±24	90±19
CON	60	M	142±32	98±15	100±22	69±11
		F	102±21	86±15	100±21	84±15
		All	124±34	92±16	100±27	75±13
	120	M	115±31	84±18	100±27	73±16
		F	93±20	72±9	100±22	78±10
		All	105±29	78±15	100±27	75±15

Values are mean ± SD in Nm. Maintenance: percent of corresponding young mean value, expressing the relative maintenance of torque in old adults.

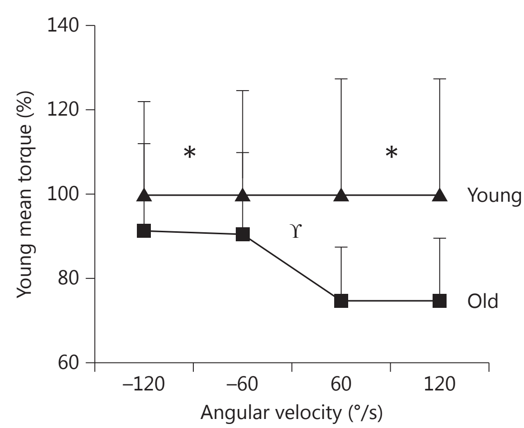

Fig. 1. Torque-velocity relationship of the quadriceps muscle with the data plotted as percentages of the mean of the young group (= 100%). The asterisks indicate significant difference from the young group ($p < 0.05$). ϒ = Significant difference between ECC and CON maintenance. Vertical bars denote SD.

tween high and low RELM individuals on gait performance at both speeds, adjusted for body height. Fifteen out of 22 variables were normally distributed and an additional 7 were too after log-transformation. Statistical analysis was done on these log-transformed variables, but the non-transformed data are presented in the Results section. IBM SPSS statistics v20 was used for all statistical analyses. Statistical significance was set at $p \leq 0.05$.

Results

Muscle Torque

Table 2 shows the non-normalized peak isokinetic muscle torques produced by males and females separately and combined and the maintenance of muscle torque for the old compared to young adults (fig. 1). There was an age (young, old) effect [$F(1, 41) = 10.29$, $p = 0.003$, $r = 0.85$], speed (4 speeds) effect [$F(2.23, 91.22) = 7.21$, $p = 0.001$, $r = 0.60$], and age by speed interaction effect [$F(2.23, 91.22) = 6.75$, $p = 0.001$, $r = 0.58$] on the isokinetic torque maintenance. There was also a significant main effect of gender [$F(1, 41) = 11.73$, $p = 0.001$, $r = 0.88$]; males were stronger than females. Tukey's post hoc analysis revealed significant ($p < 0.05$) differences in old versus young for CON and ECC maintenance and a higher ECC versus CON muscle torque maintenance (i.e., RELM). For males and females combined, RELM was 20.6%. There was no age by gender by speed interaction ($p = 0.25$); thus, RELM magnitude was similar in old males and females. There were also no age by gender ($p = 0.27$) and gender by speed ($p = 0.67$) interactions.

Gait Performance

Table 3 shows the gait performance data. With genders combined, young versus old adults performed faster at the maximal speed (all $p < 0.01$), resulting in moderate to strong effect sizes. Habitual gait performance was similar in the two age groups ($p > 0.05$).

Muscle Torque versus Gait Performance

Table 4 shows an overall (non-)task-specific relationships between averaged peak muscle torque variables (CON, ECC) and averaged gait scores based on the direction (ascent, descent, level) of locomotion. CON and ECC muscle torque predicted only maximal but not habitual functional performance significantly. CON was not a significantly better predictor of level walking than ECC in 'all' ($t = 1.67$). However, CON predicted ascending gait performance significantly better than ECC in 'all' ($t = 3.71$). Furthermore, CON predicted descending gait performance better than ECC in 'all' ($t = 2.71$) and old ($t = 2.67$). Also, CON predicted ascending gait significantly better in old compared to young ($t = 2.23$). In 'all' ($t = 0.29$) and old ($t = 0.22$), CON was not a significantly better predictor of ascending compared to descending gait performance.

Table 3. Gait performance in young and old adults

Speed	Task	Direction	Group	Young (11 F, 13 M)	Old (10 F, 11 M)	p value[a]	Effect size r[a]
Habitual	Level[b]	Level	M	1.41±0.13	1.42±0.23	0.18	0.20
			F	1.45±0.16	1.51±0.14		
			All	1.43±0.14	1.47±0.19		
	Stair	Ascent	M	12.04±1.31	11.69±1.51	0.60	0.08
			F	11.41±0.68	10.86±1.03		
			All	11.75±1.10	11.30±1.34		
		Descent	M	11.28±1.25	11.76±1.66	0.16	0.21
			F	10.49±1.16	10.66±0.68		
			All	10.92±1.25	11.23±1.38		
	Ramp	Ascent	M	3.28±0.45	3.38±0.48	0.11	0.25
			F	3.15±0.26	3.33±0.30		
			All	3.22±0.37	3.35±0.39		
		Descent	M	3.04±0.46	3.26±0.38	0.054	0.29
			F	2.99±0.41	3.14±0.31		
			All	3.01±0.43	3.20±0.35		
Maximal	Level	Level	M	2.25±0.19	1.96±0.27	<0.01*	0.44
			F	2.17±0.25	1.93±0.29		
			All	2.22±0.22	1.95±0.27		
	Stair	Ascent	M	5.97±0.52	7.67±0.75	<0.01*	0.77
			F	6.13±0.54	7.83±1.09		
			All	6.05±0.52	7.75±0.91		
		Descent	M	6.23±0.60	8.01±1.22	<0.01*	0.77
			F	6.13±0.54	8.13±0.79		
			All	6.19±0.76	8.07±1.02		
	Ramp	Ascent	M	2.10±0.22	2.42±0.48	<0.01*	0.46
			F	2.12±0.26	2.42±0.38		
			All	2.11±0.23	2.42±0.42		
		Descent	M	1.89±0.18	2.18±0.29	<0.01*	0.52
			F	1.85±0.27	2.23±0.37		
			All	1.88±0.22	2.20±0.32		

Values are mean ± SD in m/s for level walking and in s for other variables. The asterisk indicates significance. [a] Based on all young vs. old adult groups. [b] Level walking.

Table 4. Coefficients of determination for the relationship between peak quadriceps torque and gait tasks

Speed	Ascending gait vs. CON	Descending gait vs. ECC	Ascending gait vs. ECC	Descending gait vs. CON	Level walking vs. CON	Level walking vs. ECC
Habitual						
Young adults (n = 24)	0.02	0.15	0.09	0.02	0.10	0.15
Old adults (n = 21)	0.12	0.03	0.00	0.15	0.11	0.06
All[1] (n = 45)	0.00	0.00	0.01	0.04	0.04	0.02
Maximal						
Young adults (n = 24)	0.31**	0.00	0.03	0.08	0.10	0.02
Old adults (n = 21)	0.39**	0.20*	0.09	0.36**	0.07	0.04
All[1] (n = 45)	0.56***	0.16**	0.17**	0.45***	0.22**	0.09*

CON and ECC, peak concentric and eccentric quadriceps muscle torques. Ascending and descending gaits comprise of respectively stair and ramp ascent and stair and ramp descent. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. [1] Young and old adults.

Table 5. Differences in quadriceps muscle torque and gait performance between high and low RELM subgroups

	Peak torque	RELM	Group	High RELM (5 F, 5 M)	Low RELM (5 F, 6 M)	p value	Effect size r
	CON		M	84±14	96±17	0.25	0.38
			F	79±15	80±8	0.83	0.08
	ECC		M	167±27	148±30	0.27	0.37
			F	151±35	119±17	0.11	0.54
		Magnitude	M	44.6±7.5	12.0±11.0	<0.001*	0.88
			F	31.8±25.7	1.4±8.4	0.04*	0.66
Speed	Task	Direction					
Habitual	Level	Level	M	1.46±0.20	1.38±0.27	0.99	0.00
			F	1.48±0.12	1.55±0.16	0.43	0.28
	Stair	Ascent	M	11.78±1.62	11.59±1.55	0.73	0.12
			F	11.54±0.68	10.18±0.88	0.04*	0.66
		Descent	M	12.00±1.88	11.46±1.50	0.93	0.03
			F	11.00±0.45	10.31±0.74	0.15	0.50
	Ramp	Ascent	M	3.34±0.48	3.42±0.53	0.73	0.12
			F	3.46±0.37	3.19±0.10	0.16	0.54
		Descent	M	3.26±0.46	3.26±0.31	0.84	0.07
			F	3.28±0.28	2.99±0.30	0.21	0.44
Maximal	Level	Level	M	1.99±0.37	1.92±0.01	0.70	0.13
			F	1.84±0.30	2.03±0.27	0.29	0.37
	Stair	Ascent	M	7.63±0.78	7.71±0.80	0.63	0.17
			F	8.46±1.20	7.20±0.50	0.06	0.61
		Descent	M	8.00±1.53	8.03±0.91	0.96	0.02
			F	8.38±0.93	7.88±0.64	0.31	0.36
	Ramp	Ascent	M	2.47±0.64	2.37±0.24	0.81	0.08
			F	2.65±0.38	2.19±0.23	0.04*	0.65
		Descent	M	2.17±0.37	2.18±0.21	0.56	0.20
			F	2.40±0.29	2.05±0.39	0.18	0.47

Values are mean ± SD in m/s for level walking, in Nm for peak torque, in % for RELM magnitude, and in s for stair and ramp tasks. The asterisk indicates significance.

Functional Significance of RELM

Table 5 shows quadriceps muscle torque and gait performance data of high and low RELM groups for males and females separately. For high versus low RELM, the magnitude of RELM was significantly higher in males (44.6 ± 7.5 vs. 12.0 ± 11.0%, $p < 0.001$) and females (31.8 ± 25.7 vs. 1.4 ± 8.4%, $p < 0.05$). Thus, in a select group of males and females, respectively, with ~33 and ~30% greater levels of RELM, this difference beyond 30% of RELM produced no difference in level and non-level gait performances. For low versus high RELM, females performed significantly better on habitual stair ascent and maximal ramp ascent performance (both $p = 0.04$).

Discussion

We observed a lack of specificity between the type of muscle contraction-generated peak torque of the quadriceps and the type of gait tasks dominated by either CON or ECC muscle contraction. We also found no evidence that RELM, which was similar in males and females, would afford functional benefits for healthy old adults' gait performance. We discuss these findings with a perspective on how age affects the relationship between muscle strength and locomotion performance with an emphasis on ECC quadriceps muscle function.

Our peak quadriceps data are in line with previous reports in that old compared to young adults overall generated 17.3% lower peak quadriceps torques during ECC and CON contraction [1, 5–7, 15, 18] (fig. 1; table 2). Specifically, healthy old versus young adults produced 25% lower CON and 9.5% lower peak ECC quadriceps torque (both $p < 0.05$). Such reductions in maximal torque generation are in line with the evolution of age-related dynapenic weakness, most likely caused by a loss of muscle proteins [9, 10], neuronal hypoexcitability [11, 12], and an increase in tendon compliance impeding force transmission to the body levers [13, 14]. Our data also agree with previously published data with respect to the ratio between ECC and CON peak torques. In the quadriceps, the 1.4 (young males and females) and 1.7 (old males and females) ratios are numerically identical with some previously published ECC-to-CON torque ratios [1, 7, 15, 18]. The overall pattern of the peak torque and the ratio data provide a sound basis for the examination of RELM and whether or not there is specificity between the type of peak torque and the type of functional task with respect to the nature of muscle contraction and if age affects this specificity.

Young compared to old adults ambulated 17.0% faster in the 5 functional tasks when tested at the safe-fast speed ($p < 0.01$) but not at the habitual speed (difference: 1.2%). Age-related declines in habitual level walking speed are well documented [22], but there are also studies reporting a lack of age effect on gait speed [26]. Most likely, our old adults represent a highly healthy cohort suggested by the 1.47 m/s habitual level walking speed. Indeed, a previous review reported a 17% slower mean habitual level walking speed of 1.22 m/s measured at baseline of 42 intervention studies in nearly 2,500 healthy old adults [27], and other reviews also reported slower values, 1.15 [26] and 1.30 m/s [28], as 'standards' for habitual level walking speed in healthy old adults. The 1.95 m/s fast walking speed is also substantially higher than the 1.44 m/s reported in 766 similarly healthy old adults [27], or the 1.50 m/s [26], and slightly higher than the 1.90 m/s [28]; the latter two speeds were reported as 'standard'. The use of a curved measurement path and the lack of lead-in as in the Timed Up and Go and the SPPB tests produce slower gait speeds, but neither method was used in the present study. A comparison of our walking speeds measured on inclined surfaces with other studies is not possible because the measurement parameters vary widely across studies [29–32]. It seems desirable to compile normative data on stair and ramp gaits in old adults because such locomotion tasks may be even more sensitive to subtle and subclinical musculoskeletal dysfunctions, due to the high relative effort and joint torques [24, 30, 33]. Stair and ramp gaits may also predict future mobility disability more accurately than level walking in apparently healthily aging old adults.

We observed a lack of specificity between the type of muscle contraction-generated peak torques of the quadriceps and the type of gait tasks dominated by either CON or ECC muscle contraction. The expected specificity between muscle contraction type and functional performance in the locomotion tasks is conceptually well founded based on muscle mechanics [16, 34, 35], muscle activation [16, 36, 37], and metabolic cost [16, 36]. Previous studies also implied but never explicitly examined such specificity [7, 16]. Specificity is also expected because the positive and negative knee joint powers, as measured by inverse dynamics, are significantly higher during ascent and descent gaits compared to level walking [24, 29, 33]. Determining whether the associations between leg strength and gait performance are task-specific is important because dynapenia is the primary risk factor for mobility disability [8], implying that mobility disability could be more accurately predicted when peak leg muscle strength is measured in a manner that is specific than when it is not specific to a functional task.

There is a moderate association between leg strength and habitual gait speed in healthy old adults [22, 28], but our data revealed a weak or no association between these two variables (table 4). Perhaps our very healthy old adults performed the gait tasks at the habitual speed at a low relative effort so that the joint torques generated and required in these gait tasks were much lower than the previously reported ~80% of the available maximum in stair ascent and descent, minimizing the dependence on peak quadriceps torques [23]. When subjects executed the gait tasks at the safe-fast speed, quadriceps peak torque correlated significantly with gait speed in all six conditions (table 4, bottom row, R^2 range = 0.09–0.56, all $p < 0.05$). These associations were characterized by a lack of specificity between type of peak torque (ECC, CON) and type of gait (ascent, descent). The consistently higher task- and non-task-specific associations between gait performance and CON but not ECC peak quadriceps torque assign a putative role to CON effort in these gait tasks. To illustrate this, the association between ascending gait speed and CON torque was 3.5 times stronger ($R^2 = 0.56$) than the association between descending gait speed and ECC torque ($R^2 = 0.16$). Even for the non-specific comparison, the association between descending gait speed and CON peak torque was 2.6 times stronger ($R^2 = 0.45$) than the association between ascending gait speed and ECC torque ($R^2 = 0.17$) (table 4). One interpretation is that low CON peak quadriceps torque can be a limiting factor in old adults' fast gait performance on an incline. The much lower associations in the comparisons that involve ECC versus CON quadriceps peak torque, in both young and old adults (table 4), may also suggest less reliance on the quadriceps and perhaps shifting effort to ankle and hip muscles [33, 38] and the different use of the trailing leg in ascent and descent gaits [39]. A movement coordination-related factor, i.e., using a forefoot landing strategy, could also minimize the correlations between peak quadriceps ECC torque and descending gait performance by subjects shifting the reliance from the knee extensors to the plantar flexors. A different neural strategy to control balance during ascent and descent could also contribute to these lower associations. For example, muscle coactivity of the knee flexors and extensors is 2.0 and 1.4 times greater in old versus young adults during stair descent and ascent, respectively [23]. An increase in coactivity possibly serves as a functional mechanism to maintain limb and joint stiffness [40], as old adults have less functional 'reserve' to compensate for sudden unexpected perturbations, especially during demanding and hazardous ADLs like stair and ramp negotiation. These speculations require confirmations.

Over the past 3 decades, numerous studies reported on the phenomenon of RELM [7, 15, 16, 19]. There are striking examples for the age-related sparing of peak voluntary ECC muscle torque, as in one study, where old adults actually produced numerically almost identical ECC plantarflexion [17] vis-à-vis the 30–50% lower peak isometric or CON torques [15]. In the present study, the difference in peak CON quadriceps torque between young and old adults was 25%, whereas the difference in ECC torque was 9.5%, documenting RELM in the present sample qualitatively to about the same extent as reported previously [7, 15, 16], based on the computation of RELM [16] (discussed extensively in our data analysis section).

For the first time, we examined whether or not RELM affords functional benefits when old adults walk on level and inclined surfaces. To amplify any potential effects of RELM, we created subgroups of healthy old males and females with ~33 and ~30% greater levels of RELM than other subgroups of the same age, accompanied by large effect sizes of r = 0.88 and 0.66 (table 5). Against the hypothesis, after careful examination of table 5 (absolute torques and RELM), high RELM and higher ECC muscle function, in particular for the women, did not translate into higher gait speed measured on level and inclined surfaces between these subgroups of healthy old adults. In women, even the high versus low RELM group performed significantly worse on habitual ascending stairs and fast ascending a ramp (both p = 0.04). The previously discussed lack of specificity between the type of peak quadriceps torque and type of gait task foreshadowed the absence of RELM effect on locomotor function, but the near nil effect of RELM on performance in descending gaits (effect size range: 0.02–0.50) is rather unexpected (table 5). Considering that improving ECC leg muscle function by various forms of ECC training resulted in improved gait speed [41, 42], balance [41], and fall risk [41, 43], it is as reasonable to expect that high ECC function as quantified in the present study, especially through the high RELM subgroup, would provide an agreement with improved functional outcomes reported in interventions studies.

One reason for a lack of RELM effect on gait function could be that even though the RELM subgroups differed in RELM itself, subjects in the subgroups were similar in peak ECC and CON quadriceps torque (table 5). Perhaps larger sample sizes would have allowed us to detect the expected effects of RELM on gait function (table 5). Even though quadriceps strength has been promoted as a key contributor to locomotion, the recent concept of biomechanical plasticity in old adults' gait [22, 44] shifted attention to the observation of a preferential reduction in ankle plantarflexion function even in healthy old adults, an outcome we did not measure in the present study.

In conclusion, the present study confirmed previous findings of RELM, but found no evidence for specificity in the associations between the type of muscle contraction (ECC, CON) and the type of gait task (descent, ascent), and also found no evidence that normal and 30% above normal levels of RELM would increase or predict healthy old adults' gait performance on level and inclined surfaces. Future work should examine if RELM is associated with a heightened performance in other measures of neuromuscular function such as gait biomechanics, muscle activation, as well as rate and control of voluntary force development in old adults with high or low mobility.

Disclosure Statement

The authors declare no conflicts of interest.

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